Relative Frequencies of Blue Stragglers in Galactic Globular Clusters: Constraints for the Formation Mechanisms[1]

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ABSTRACT

We discuss the main properties of the Galactic globular cluster (GC) blue straggler stars (BSS), as inferred from our new catalog containing nearly 3000 BSS. The catalog has been extracted from the photometrically homogeneous V vs. $(B-V)$ color-magnitude diagrams (CMD) of 56 GCs, based on WFPC2 images of their central cores. In our analysis we used consistent relative distances based on the same photometry and calibration. The number of BSS has been normalized to obtain relative frequencies ($F_{\rm BSS}$) and specific densities ($N_{\rm S}$) using different stellar populations extracted from the CMD. The cluster $F_{\rm BSS}$ is significantly smaller than the relative frequency of field BSS. We find a significant anti-correlation between the BSS relative frequency in a cluster and its total absolute luminosity (mass). There is no statistically significant trend between the BSS frequency and the expected collision rate. $F_{\rm BSS}$ does not depend on other

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cluster parameters, apart from a mild dependence on the central density. PCC clusters act like normal clusters as far as the BSS frequency is concerned. We also show that the BSS luminosity function for the most luminous clusters is significantly different, with a brighter peak and extending to brighter luminosities than in the less luminous clusters. These results imply that the efficiency of BSS production mechanisms and their relative importance vary with the cluster mass.

Subject headings: stars: blue stragglers — globular clusters: general — stars:luminosity function — Hertzsprung-Russell diagram

1. Introduction

Globular Clusters (GCs) are important astrophysical laboratories for investigating the stellar dynamics and stellar evolution of low-mass stars (e.g., Meylan & Heggie 1997). In recent years, it became clear that we can not study these two astrophysical processes independently if we want to understand GCs and properly address several long-standing problems concerning their stellar content.

Among the most puzzling products of the interplay between stellar evolution and dynamics are the blue straggler stars (BSS). This group of stars was originally identified by Sandage (1953) in the cluster M3 as a bluer and brighter extension of the main sequence (MS) turn-off (TO) stars. At present, the most popular mechanisms suggested to account for their origin are *primordial binary evolution* (McCrea 1964), i.e., mass transfer and/or coalescence in primordial binary systems (Carney et al. 2001), and *collisional merging*, i.e., the collision of single and/or binary systems (Bailyn 1995). Unfortunately, current photometric investigations do not allow us to figure out the mechanism that triggers the formation of BSS in GCs, and indeed it has been suggested that both primordial binary evolution and collisions are probably at work in different clusters (Ferraro, Fusi Pecci, & Bellazzini 1995; Piotto et al. 1999, Ferraro et al. 2003), or even within the same cluster (Ferraro et al. 1997). The observational scenario concerning BSS formation has been recently enriched by the results of a spectroscopic survey by Preston & Sneden (2000, hereafter PS00). On the basis of multi-epoch radial velocity data of field blue metal-poor (BMP) stars, PS00 found that more than 60% of the stars in their sample are binaries. On the basis of empirical evidence, PS00 concluded that at least 50% of BMP stars are BSS. Moreover, PS00 suggested that the BSS

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[1]Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

in their sample must have formed via mass transfer in binaries. Finally, PS00 found that the specific frequency of BSS in the local halo is an order of magnitude larger than in GCs. This discrepancy opens several new questions concerning the origin of field and cluster BSS.

In an attempt to better understand the properties of BSS stars in GCs, we took advantage of our homogeneous database of color-magnitude diagrams (CMD) from WFPC2 images (Piotto et al. 2002) to select a sample of nearly 3000 BSS in 56 GCs characterized by different morphological and dynamical properties. In this paper we exploit the new BSS catalog to investigate empirically whether the BSS population is related to any of the properties of the parent GC. Here we present the results we believe to be the most relevant and original. The entire BSS photometric catalog and further details on the BSS extraction will be published in a forthcoming paper (De Angeli et al. 2004), and it will become available at the Padova Globular Cluster Group web site.

2. THE DATABASE OF BSS IN GCs

We have recently completed our HST/WFPC2 snapshot project (GO 7470, GO 8118, GO 8723). By adding the data from our former GO 6095, and similar data from the archive (i.e., WFPC2 images collected in the cluster center, in the F439W and F555W bands), we have obtained a total of 74 CMDs. They can be found on the Padova Globular Cluster Group web pages (http://dipastro.pd.astro.it/globulars). Details on the data reduction are in Piotto et al. (2002). Here suffice it to say that all the data have been processed in the same way: instrumental photometry with DAOPHOT/ALLFRAME, CTE correction and calibration to the B and V standard systems following Dolphin (2000). Artificial star experiments have been run for all the clusters to estimate the completeness of star counts. Completeness corrections have been always applied when necessary. For the BSS sample the completeness was typically larger than 90%.

BSS are present in all 74 GCs of our catalog. However, 18 CMDs were too contaminated by background/foreground stars, or heavily affected by differential reddening, to allow us a reliable selection of BSS. The final catalog, includes 2798 BSS candidates in 56 GCs (actual stars, before completeness correction), i.e., about five times the number published in previous catalogs (Fusi Pecci et al. 1993; Sarajedini 1993).

The BSS in our sample share one common feature: in the inner region mapped by our WFPC2 images, the radial distribution of BSS is more centrally peaked than that of any other cluster population. In fact, we performed several Kolmogorov-Smirnov tests on the radial distributions of HB, RGB, and BSS, and we found that the BSS are more centrally

concentrated at the level of 99.9%, apart from a few cases where the small number of stars prevents any statistically significant test.

3. THE RELATIVE FREQUENCY OF BSS

In this section, we investigate whether the number of BSS is correlated with any of the physical and morphological parameters of their parent GCs. In order to compare the number of BSS in different GCs properly, we must adjust it to allow for how much of each cluster we sampled. To this end, a number of different specific frequencies (defined as the ratio between the number of BSS and a reference population) have been used in the literature (cf. Ferraro et al. 1995). We estimated the specific frequencies by normalizing the number of BSS to the HB ($F_{\rm BSS}^{\rm HB}$) or the RGB ($F_{\rm BSS}^{\rm RGB}$) stars. Interestingly, the results discussed below do not depend on which specific frequency we choose. Therefore, in the following we will adopt $F_{\rm BSS}^{\rm HB}$, and will refer to it as $F_{\rm BSS}$. The numbers of BSS and HB stars have been corrected for completeness (details in Piotto et al. 2002) before calculating $F_{\rm BSS}$.

The top panel of Fig. 1 shows $F_{\rm BSS}$ as a function of the integrated visual absolute magnitude of the cluster, from the integrated visual apparent magnitudes and the reddening values in the Harris catalog and the apparent distance moduli derived by Recio-Blanco et al. (2004a) for the same clusters by following the procedure outlined by Zoccali et al. (2000). Even though the distribution of empirical data still shows a large scatter for $-8 \leq M_V \leq -7.4$, the data in this panel clearly show a correlation between $F_{\rm BSS}$ and the integrated absolute magnitude M_V. In particular, the faintest clusters in our sample, namely NGC 6717 and NGC 6838, present a BSS specific frequency that is more than a factor of 20 larger than that for the brightest clusters. This result is in agreement with that found by PS00 on the basis of data collected from the literature for 30 GCs though their plot tends to flatten for $M_V < -7$, while Fig. 1 shows that $F_{\rm BSS}$ decreases continuously with increasing cluster total luminosity, up to $M_V < -9$. Interestingly enough, PCC clusters (open circles), with the exception of NGC 5946 that shows a small value of $F_{\rm BSS}$, behave as normal clusters.

The middle panel of Fig. 1 shows that $F_{\rm BSS}$ also depends on the cluster central density ρ_0 (in $L_\odot/pc^3$), though this correlation is statistically somewhat less significant than the previous one. (For internal consistency, we have re-calculated the central densities using the equations suggested by Djorgovski (1993), but adopting our new distance moduli and the central surface brightness in the Harris catalog.) The $F_{\rm BSS}$ for clusters with $\log \rho_0 > 3.2$ shows a large dispersion, and no correlation. For $\log \rho_0 < 3.2$, the BSS frequency increases with decreasing central density. Once again, the PCC clusters do not show any peculiar trend. We have also compared $F_{\rm BSS}$ with the concentration parameter c and the half mass

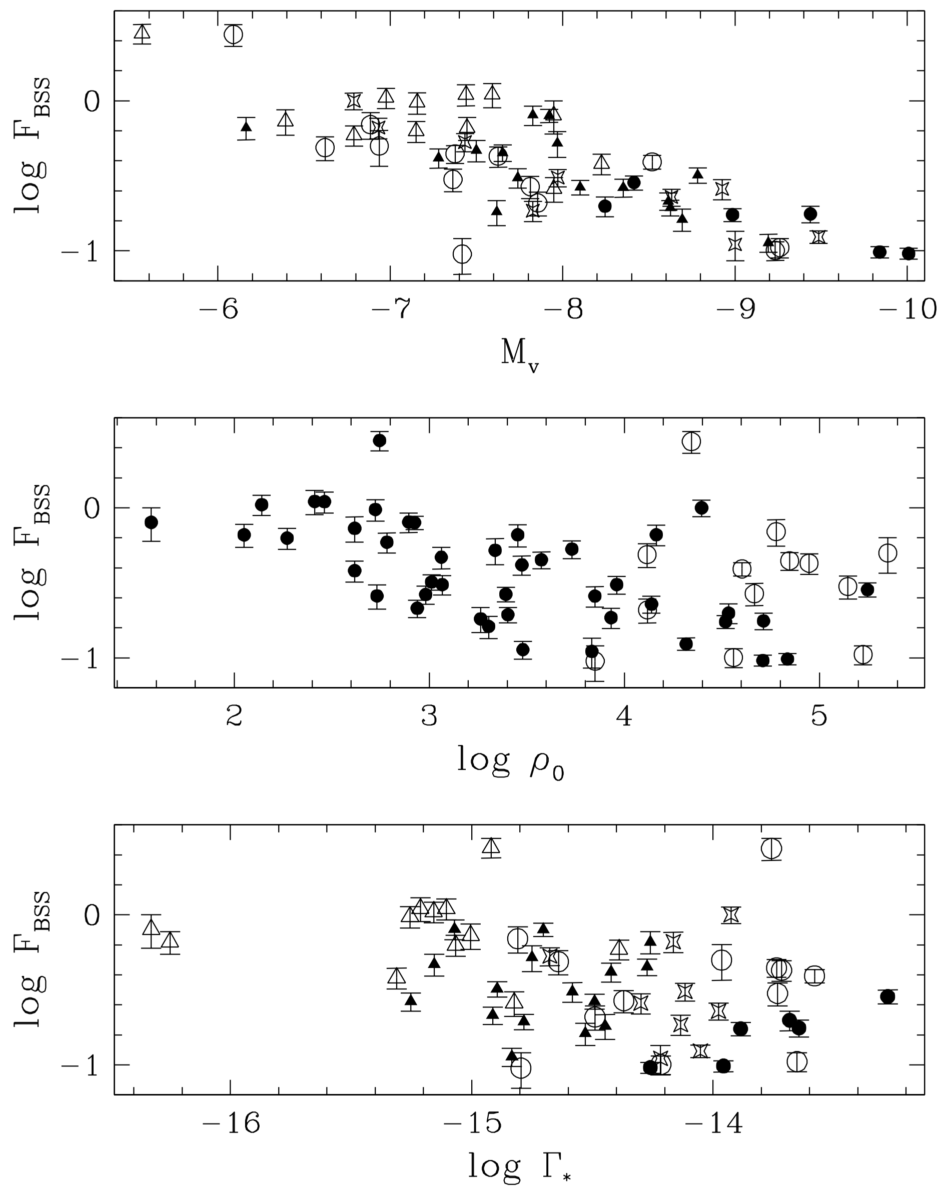

Fig. 1.— BSS relative frequency as a function of the integrated absolute magnitude of the cluster (*top panel*), the central density (*middle panel*), and of the collision rate (*bottom panel*). Different symbols are used (in the top and bottom panels) for clusters with different central densities: $\log \rho_0 < 2.8$: *open triangles*; $2.8 < \log \rho_0 < 3.6$: *filled triangles*; $3.6 < \log \rho_0 < 4.4$: *crosses*; $\log \rho_0 > 4.4$: *filled circles*. In all panels, PCC clusters are open circles.

relaxation time $t_{\rm h}$. Here too there is no clear correlation, though GCs with $\log t_{\rm h} < 9$ have, on average, a $F_{\rm BSS}$ three times larger than clusters with a longer relaxation time.

In view of the proposed formation mechanisms for BSS, it is interesting to check whether the $F_{\rm BSS}$ depends on the expected frequency of stellar collisions. King (2002) demonstrated that the rate of stellar collisions (per cluster and per year) in a King model GC is about $\Gamma_{\rm c} = 5 \times 10^{-15}(\Sigma_0^3 r_{\rm c})^{1/2}$, where Σ_0 is the central surface brightness in units of $L_{\odot V}$ pc^{-2} (equivalent to $\mu_v = 26.41$), and $r_{\rm c}$ is the core radius in parsecs (taken from Harris 1996). In order to calculate the probability $\Gamma_\star$ that a given star will have a collision in one year we have divided this collision rate by the total number of stars ($N_{\rm star}$) in the cluster. This has been estimated by using the integrated visual absolute magnitude of the cluster, assuming $M/L = 2$ and a typical mass for the colliding stars of $0.4 m_\odot$. The bottom panel of Figure 1 plots $F_{\rm BSS}$ as a function of the resulting $\Gamma_\star$. There is no statistically significant correlation, though we note that, on average, the 11 clusters with the smallest collision probability ($\Gamma_\star < 10^{-15}$) have a BSS frequency 2–3 times higher than clusters with higher collision rates. It must be noted here that, according to the results by PS00, the BSS frequency of the GCs with the smallest collision probability in our sample is about 5 times smaller than the BSS frequency in the field, where collisions are so much rarer. We note that in the case of PCC clusters, the current values $\Gamma_\star$ and ρ_0 may not be representative of the average dynamical environment in which currently–observed blue stragglers have formed. However, Fig 1 shows that PCC clusters have BSS frequencies comparable to normal King–model clusters, possibly indicating that their dynamical evolution has not affected in a significant way the BSS formation.

The anti-correlation between $F_{\rm BSS}$ and total cluster luminosity, the lack of a statistically significant correlation with the collisional parameter, and the apparently higher relative frequency of BSS where collision rates are very small are the most interesting results extracted from our catalog. These empirical facts are somehow puzzling. In fact, we would have expected more BSS in clusters where the probability of collision is higher. We will discuss these results further in the next Section.

The error bars plotted in Fig. 1 account for Poisson sampling errors and the uncertainty in the completeness corrections. Even if we assume an upper limit of 0.2 magnitude for the uncertainties in the individual distance moduli, the correlation shown in Fig. 1 represents a robust empirical result, and the reasons are manifold. Unlike other data available in the literature, i) our dataset is photometrically homogeneous; ii) the star counts included the 2 innermost arcmin; iii) the star counts of BSS and of the reference populations have been corrected for incompleteness. As a whole, the present dataset is only very marginally affected by the thorny statistical problems affecting previous estimates of BSS specific frequencies

(cf. discussion in Ferraro et al. 1995).

4. DISCUSSION

The statistically significant anticorrelation of the BSS relative frequency with the integrated luminosity and the independence of the expected collision rate discussed in the previous Section are noteworthy, and we will concentrate on them. These observational facts are complemented by the finding by PS00 that field BSS have a frequency $F_{\rm BSS} = 4.0$, an order of magnitude larger than the BSS frequency of the bulk of the GCs.

Figure 2 shows the same results of Fig. 1, in a different way that may be more enlightening. Here we look at the number of BSS, HB, and RGB stars relative to the total flux in the same region. We call this quantity $N_{\rm S}$; it is defined by

$$\log N_{\rm S} = \log \left[\frac{N}{(F_{\rm HST}/10^{-0.4V_{\rm tot}})} \cdot \frac{1}{10^{-0.4M_V}} \right],$$

where N is the total number of BSS (or HB or RGB) stars, corrected for completeness, $F_{\rm HST}$ is the total flux from all the stars that we measured in the region, $V_{\rm tot}$ is the integrated apparent magnitude of the cluster, and M_V is its integrated absolute magnitude. (Note that our CMDs typically extend well below the turnoff, so that the contribution from the fainter stars is negligible.)

The first factor in the brackets can be understood as follows: the quantity $F_{\rm HST}/10^{-0.4V_{\rm tot}}$ is the fraction of the total cluster flux that is sampled by the HST field. If the BSS were distributed like the flux, then $N/(F_{\rm HST}/10^{-0.4V_{\rm tot}})$ would be the number of BSS we would expect if we could observe the whole cluster. In fact, as the BSS are more concentrated to the center than is the flux, the quantity above is still a reasonable approximation to the total number of BSS to be expected. The defect in the approximation increases the scatter in $N_{\rm s}$, but it does not introduce any systematic effects, since (as we have verified) there is no correlation between the fraction of flux included and M_V. The second factor in the brackets is just our previous normalization to the size of the cluster, but now in luminosity units.

Interestingly enough, Fig. 2 confirms that the HB and RGB stars are very good tracers of the cluster population, as their absolute density remains constant over more than 4 magnitudes in cluster total luminosity. This fact removes the risk that the results of Fig. 1 might be due to some anomalous gradient in the distribution of HB and RGB stars (cf. Djorgovski, Piotto & Capaccioli 1993). Figure 2 confirms that the density of BSS decreases with increasing total cluster mass and that there is no correlation between the density of BSS and the collisional parameter. However, we note that, given the small size of the error bars,

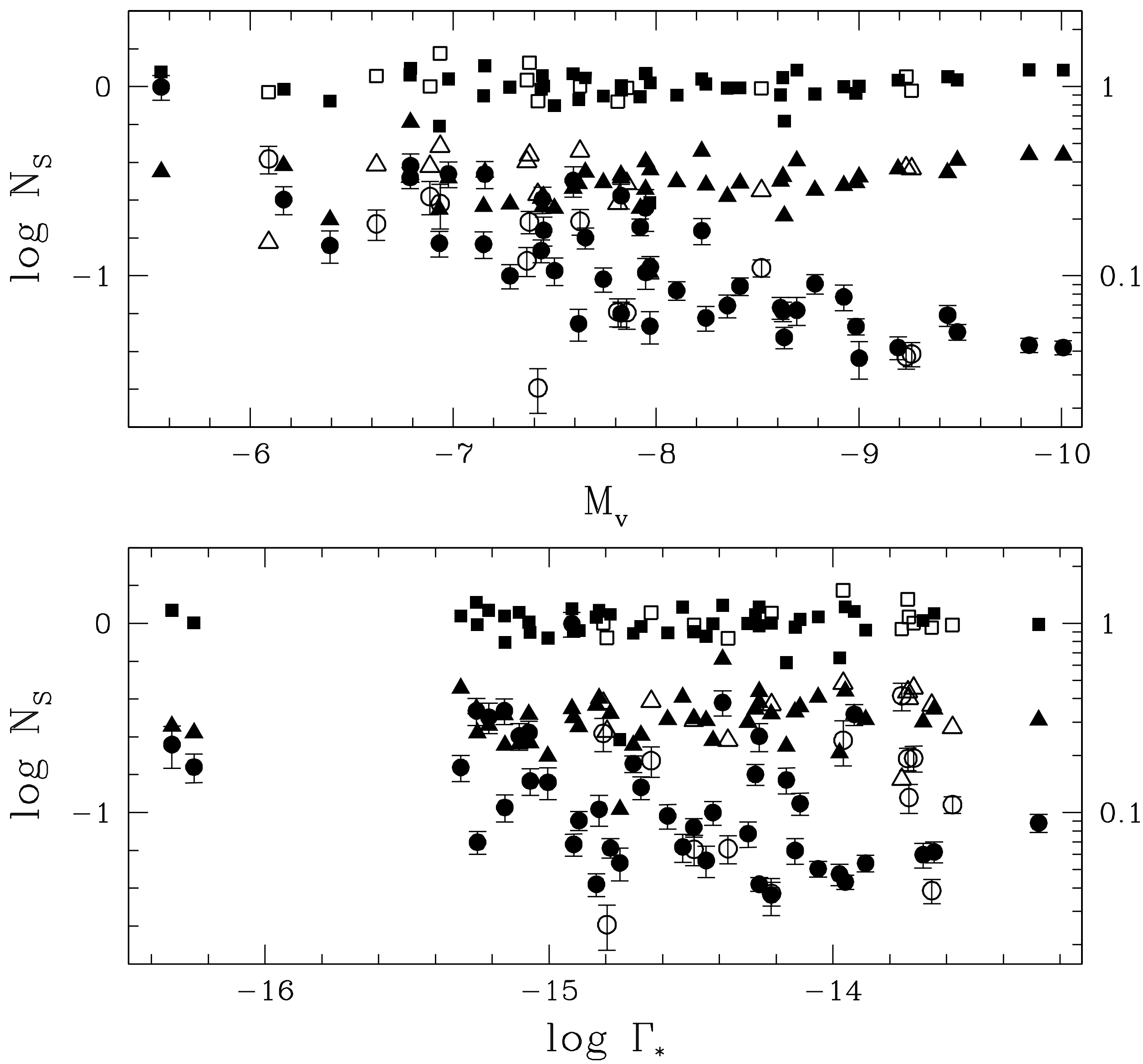

Fig. 2.— Number of BSS (circles), HB (triangles), and RGB (squares) stars per absolute visual flux unit as a function of the integrated cluster magnitude (*top panel*) and of the collision rate (*lower panel*). Open circles represent PCC clusters.

the dispersion of the the BSS density is much larger than the dispersion of the HB and RGB star densities, and that, as noticed in Fig. 1, clusters with $\Gamma_\star < 10^{-15}$ have a 2–3 times larger BSS density than clusters with higher collision rates. The lack of an overall dependence of $F_{\rm BSS}$ and N_s on the collisional parameter seems to suggest that direct collisions of single or binary stars are not the main formation mechanism of BSS. At first glance, the evolution of primordial binaries also does not seem to be the dominant formation mechanism for BSS in all GCs. In the simple hypothesis that the binary fraction is the same in all clusters, we would expect the BSS density to show a behavior similar to that of the HB and RGB stars, in Fig. 2. On the other hand, the evolution of primordial binaries is affected by the cluster environment, and, in particular, it is accelerated in clusters where the encounter probability is higher. Indeed, in a paper parallel to this one, using the mechanism proposed by Davies & Hansen (1998) to explain the production of millisecond pulsars in GCs, Davies, Piotto, & De Angeli (2004) demonstrate that in clusters with high encounter probability the formation of BSS from primordial binaries has been favored in the past. Now these binaries cannot form BSS anymore (they have already evolved), and this explains the observed relative absence of BSS in many high mass, high collision rate clusters. It also explains the relatively larger fraction of BSS among the field stars, where the even lower-density environment makes the evolution of binaries via encounters slower than in any GC, allowing them to produce BSS for a more extended time interval (till the present).

Davies et al. (2004) show also that only in the most luminous GCs (specifically, clusters with $M_V < -8.8$) do the BSS start to be produced predominantly by stellar collisions. A better way to characterize the physical properties of the BSS is to look at their luminosity function (LF). In order to overcome possible dependencies of the LF on the cluster metallicity, distance, and reddening, we have divided the luminosity of each BSS by the turn-off luminosity of the parent cluster. Figure 3 shows the LFs for GCs with different total luminosity. The cut in M_V has been set at $M_V = -8.8$, where the theory (Davies et al. 2004) predicts that the BSS should become predominantly collisional.

Interestingly enough, clusters with $M_V < -8,8$ have a BSS LF which is significantly different from the BSS LF of less luminous clusters (Fig. 3), in that the LFs for the most luminous clusters have a brighter peak and are significantly shifted toward brighter magnitudes. If the relative importance of the BSS production mechanisms depends on the cluster mass, we would then expect to see a dependence of the BSS LF on M_V, as is observed in Fig. 3. In general, a BSS produced by collision is expected to have a different luminosity with respect to a BSS from mass transfer or merger of binaries, due to the resulting interior chemical profile. How much different is still controversial. Indeed, recent detailed smoothed particle hydrodynamic simulations performed by Sills et al. (2002) have shown that collision products are not chemically homogeneous. This has the effect of producing a BSS structure

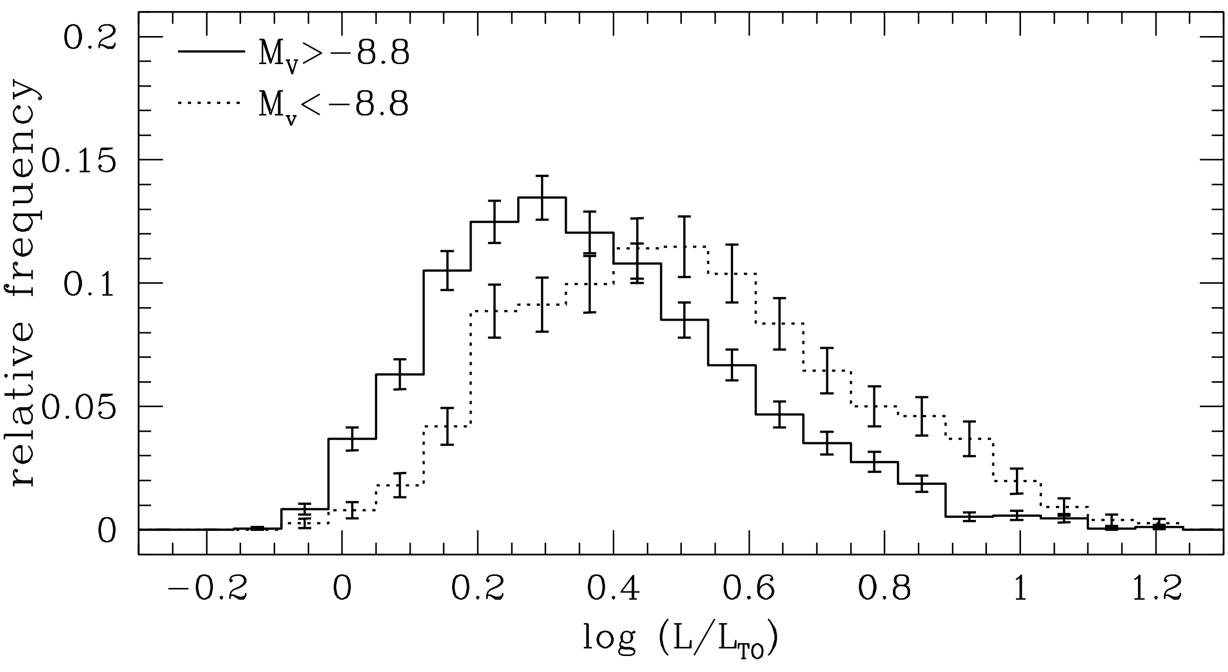

Fig. 3.— BSS LFs for clusters with different integrated magnitude.

less blue and less bright than expexted on the basis of the 'fully mixed' models (e.g., Bailyn & Pinsonneault 1995). Nevertheless, Sills et al. (2001) have also shown that collision products emerge as rapidly rotating blue stragglers, and so far we lack a full understanding of the changes in the evolutionary properties due to rotationally induced mixing.

It is also worth noting that PCC clusters seem to have normal BSS population. This might be due to the fact that the core collapse phase is very short, and confined to the very central part of the clusters, and therefore does not affect the BSS production over the last few Gyr.

This research was supported by the Ministero dell'Istruzione, Università e Ricerca (PRIN 2001 and PRIN 2002), and by the Agenzia Spaziale Italiana. I.R.K. and S.G.D. acknowledge the support of STScI Grants GO-6095, 7470, 8118, and 8723.

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